Concept for Inclusion of Analytical and Computational Capability in Optical Plume Anomaly Detection (OPAD) for Measurement of Neutron Flux

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abstract—Researchers are working on many fronts to make possible high speed, automated classification and quantification of constituent materials in numerous environments. NASA's Marshall Space Flight Center has implemented a system for rocket engine flow fields/plumes; the Optical Plume Anomaly Detection (OPAD) system was designed to utilize emission and absorption spectroscopy for monitoring molecular and atomic particulates in gas plasma. An accompanying suite of tools and analytical package designed to utilize information collected by OPAD is known as the Engine Diagnostic Filtering System (EDIFIS). The current combination of these systems identifies atomic and molecular species and quantifies mass loss rates in H2/O2 rocket plumes. Additionally, efforts are being advanced to hardware encode components of the EDIFIS in order to address real-time operational requirements for health monitoring and management.

This paper addresses the OPAD with its tool suite, and discusses what is considered a natural progression: a concept for migrating OPAD towards detection of high energy particles, including neutrons and gamma rays. The integration of these tools and capabilities will provide NASA with a systematic approach to monitor space vehicle internal and external environment.

TABLE OF CONTENTS

1. DATA COLLECTION AND PROCESSING

Currently, the transducer is a digitizing spectrometer of one form or another. For the first several years, OPAD instruments relied upon custom hardware produced at Arnold Engineering Development Center (AEDC). This was because hardware with the necessary capabilities simply did not exist at the time. More recently, the systems have come to rely upon ruggedized versions of spectrometer units produced commercially.

Light from the engine plumes is collected and presented to the spectrometers by means of lens assemblies and/or a UV-grade quartz optical fiber, either in single or bundled form. The lens assemblies, or telescopes, were mounted off of the engine for most of the early test stand systems, but have been mounted directly to the engine nozzles in many of the more recent tests, or on the engine shield ("eyeball") in the case of the DC-XA [1].

Several different hardware platforms have existed through the lifetime of the OPAD effort. Here, too, early systems were custom built and programmed; usually, these were DOS or Windows systems on some version of a personal computer (PC). Up until recently, the spectrometer output was still in analog form, so the data system was required to provide analog-to-digital conversion (A/D) in addition to data manipulation and storage. Data collection has since been simplified with commercial off-the-shelf (COTS) solutions, such as USB spectrometers that deliver a digitized scan of data as quickly as once every 13 microseconds through a standard USB interface on a laptop.

Unfortunately, a standard PC won't qualify for flight. So as techniques have evolved, it has also become necessary to pursue improvement of the hardware used, with an expectant eye toward future flights. For this reason, OPAD systems have been considered on such platforms as PC/104, VME, and Compact PCI, with both Intel 80x86 and PowerPC processors. Various enclosures have been used, ranging from custom to semi-custom. Frequently, the availability of extended temperature (-40 to +85 C) and vibration-tolerant versions of hardware has been a driving factor in selection.

The advancement of solid-state memory technology has created great interest over the course of the last several years. Rotating media in conventional hard drives is simply incapable of withstanding launch conditions and difficult to keep operational in the vacuum of space. As a result, more recent versions of OPAD have come to contain substantial amounts of Flash disk and other solid-state media.

Through most of the testing so far, learning to understand and exploit the capabilities of the spectrometer units has as a matter of necessity taken second seat to discovering and adapting for the intricacies of data collection. As a result, implementation of some improvements has been delayed. . Because the spectrometers used are of an integrating type, signal collection takes place over a selectable period of time before being output. If the period is too short, the output signal doesn't encompass enough range to be significant. If the period is too long, some or all of the scan will exceed the maximum level, or "saturate." Auto-scaling features are being explored.

System calibration has been and continues to be an important consideration. For calibration on the launch pad, both absorption and emission systems benefit from handheld calibration units applied at the vehicle; various configurations of these have been used in the past, with integrating spheres the current favorite. These spheres can be placed directly in front of the optics on the vehicle, controlling the entire field of view and eclipsing external influences on the calibration.

In-flight self-calibrating features have also been explored. Possible hardware configurations include bifurcated fiber carrying calibrated light directly to the spectrometer on one half-circuit, with the source itself packaged safely elsewhere on the vehicle. The known signal could alternate with or supplement the signal received through the plume on the other half. Similarly, past tests have included a UV-emitting LED in part of the field of view, so that with an additional level of analysis, signal loss due to any of several factors can be quantified.

Additional knowledge of the spectrometer's more subtle behavior can yield useful information. Currently, the OPAD systems utilize COTS hardware from Ocean Optics, Inc. The sensor unit's array is configured to measure 2048 data points simultaneously. Some of these pixels are masked from exposure to input light; however, these "dark pixel" positions in the array still output measurable signal. While such information is useful for a baseline with which to compare the deviation of the active pixels, all of the pixels' outputs change with variation in the ambient temperature at the array. Ocean Optics has been involved in characterization of the thermal response of dark pixels in order to allow temperature compensation algorithms to be implemented.

The methods for detecting oddities in a given scan in order to validate it are not particularly difficult. Saturation of an individual pixel occurs any time that pixel's analog output reaches (or exceeds) the maximum binary range of the A/D. Complete saturation occurs when most or all of the pixels in the wavelength range of interest saturate. In the former case, some compensation may be possible in order to extract useful information from the scan; in the latter case, the entire scan must be invalidated. In either case, it might be desirable to decrease the spectrometer's integration period for ensuing scans.

Characterization of the baseline of a scan, or even the dark pixels' behavior, is more of a statistical issue. Again, this is not necessarily difficult to accomplish, but it does require the examination of most or all of the pixels in several consecutive scans. The average underlying level of the overall scan is determined and typically subtracted from the "raw" data during preprocessing. Compensation is also made for "hot" pixels -- array locations that not only seem to be uncharacteristically active, but also are unique to individual spectrometer units.

Part of the problem with including these desirable functions in real-time has been that the processing capability of the system can be taxed just keeping up with the spectrometers' data output rate. The simple fact that the spectrometers are integrating units and deliver their pixel data serially means that each scan is already somewhat out of date by the time it arrives in the initial raw data storage. Also, if a change is made to a spectrometer's scan parameters, it will take effect, at the earliest, after the scan currently underway finishes. Add to this the time it takes to preprocess, characterize and analyze scans, as necessary, and it quickly becomes obvious that the conventional definition of "real-time" is being stretched somewhat.

While redesigning the spectrometers to provide all of the pixels' outputs in parallel might seem the ideal choice, it would require an A/D for each of thousands of pixels in a single scan. This is not a practical option, at least for the near future. However, until such technological advances become available, there do exist other feasible approaches.

Processing hardware is constantly being updated and improved. While available processor (CPU) speeds do not typically match those available in commercial personal computers, they are at least continually increasing. With requirements for extended temperature capabilities and other ruggedized features, the choices are narrowed much further. But, happily, many more companies are starting to provide a selection of robust COTS hardware with much more general-purpose functionality. Hardened units with Intel 'x86 processors are still running at between 500 MHz and 1 GHz., but the fact that such processors cannot typically be qualified for flight has led to efforts to assemble a cPCI system with PowerPC processors running at 300 MHz. Since this new system utilizes a higher-speed bus, data transfer will be expedited substantially. Additional features, such as built-in-test (BIT) capability and watchdog timers providing better hardware and software safeguarding, are also becoming more commonly available on the commercial market.

Another method to increase system processing power breaks down tasks and delegates them to multiple processors. For the OPAD system, parallel processing comes somewhat naturally because many of the operations are already segregated. Data collection and preprocessing are fairly self-contained, while the EDIFIS functions also break down into three or so distinct operations. For this reason, the cPCI system will be built from perhaps four or more CPU cards, each tasked for different portions of the system's overall function.

Operating system (O/S) choices present another field of options. In the past, OPAD data collection has relied almost entirely upon Microsoft products. But even while 'x86 processors were the only CPUs utilized, thought was being given to beneficial change. Since non-Intel products came under consideration, the drive toward other O/S selections has heightened. Additionally, O/S source code requirements preclude the use of protected software. Linux, and specifically some variety of Real-Time Linux, has come to be the preferred O/S. Besides having a lower processing overhead and a reputation for robustness and flexibility, Linux is on the cutting edge for embedded deployment.

2. DATA ANALYSIS TECHNIQUES

Much of what has been discussed so far for data system development applies equally to the EDIFIS subsystem. Faster hardware, parallel processing, and improved O/S selection have impact here, too. Getting the analysis package built into and operational with the data collection subsystem will be no small accomplishment. But improvements specific to the EDIFIS are also planned, some of which are fairly new and exciting technologically.

One subtask of the EDIFIS will be scan validation. Similar in concept to preprocessing functions in the data collection subsystem, this will involve checking the entire scan or a set of scans for reasonableness. It would capture data hazards such as stray inputs from launch pad lights or the sun or data collection glitches. Validated scans will be fed to the Event Detector subtask. This portion of analysis will be responsible for determining if optical energies evident in the data represent significant anomalous events rather than normal operation of the engine. It should be noted here that some ability to quantify the material species detected must be possible in order to make the system work. This is important because the relationship of wavelength peak levels in the spectrum to corresponding quantities of material being output in the plume is not linear amongst species densities.

The job of predicting a spectrum given an itemization of materials input to the plume is not nearly as difficult as the reverse operation [2]. Another subtask of the EDIFIS involves a neural network using each spectral input to make an initial content estimate. This is fed into an iterative algorithm [3,4], which repeatedly makes a spectral prediction, compares it with the spectral input, and adjusts the estimate, until a nearly identical comparison is reached. The neural network's estimate significantly reduces the number of iterations of the algorithm and total time required to produce the final results.

Since the neural network only exists at this time as a software model, one current goal is to produce a viable hardware version. The objective is further increased speed in producing the output estimate from the neural network. Initial estimates are that this speed increase could be a few orders of magnitude.

Multiprocessor systems are one form of parallel computing. Another relatively young variety is parallel and dynamically reconfigurable computing done in the form of field programmable gate arrays (FPGAs) or other reprogrammable devices reproducing individual CPU operations in numerous specialized clusters, as needed.

Gate counts on available devices now number in the tens of millions, and the technology is advancing rapidly. Conceivably, an entire logic network for the EDIFIS will eventually fit on a single chip -- with room for the data collection system almost as an afterthought!

Studies are underway at MSFC utilizing a new breed of computer that capitalizes on FPGAs. StarBridge Systems produces what they call a Hypercomputer, with arrays of FPGAs and the accompanying software and hardware necessary to program them for almost any conceivable purpose, and to test the results. External connections can also be made to the array for physical testing of the logic configured. VIVA, the graphical programming language with their system, possesses many of the versatile features of other popular programming languages: objects, polymorphism, and recursion, for instance. The software controls code compilation, synthesis, FPGA programming, and graphical control and display of testing. Support for interfacing to other languages such as C++ and VHDL is being implemented.

Exploratory work with digital signal processors (DSPs) is also being pursued. Some of these devices are very small, relatively inexpensive, and mathematically powerful. If several were wired together in the specific configuration of the EDIFIS neural network, a modestly reconfigurable hardware version of the network could be produced. Unfortunately, the devices currently under consideration also have a reputation for not working well together, and massive interconnectivity is crucial to building a neural network.

The most advantageous results from the current incarnation of the OPAD system are really only attainable provided detailed knowledge exists of the system under test. An intimate understanding of not only the materials used in all of an engine's components but also the physics of its operation is critical. The field of view of the optics, probe location(s), and flight conditions all combine to influence results. Some very intricate science goes into making the measurements needed.

As with many new technologies, a total-systems approach is integral to overall success. An optimal scenario for future application of OPAD technology to engine diagnostics and health monitoring requires involvement of the OPAD team in the design of a target engine and vehicle from the start. Rather than install probes or collection optics on the engine wherever they will fit, collection optics and related hardware would be physically and functionally integrated into the vehicle system. This could mean moving the probes from the nozzle lip up into the walls of the engine nozzle, combustion chamber, or other flow-field path. Or it could mean something as simple as building protected paths for the optical fibers into the exterior of the engine. But it has become increasingly apparent over the years that retrofitting most existing engines and vehicles can be challenging or impractical.

A slightly more ambitious option for integrating an OPAD system into a vehicle's design requires going back even further in the design process, with a technique that has come to be referred to as "doping" or "tagging." By incorporating materials science technology early on that would allow unique trace ions to exist in component alloys, particularly those of a critical nature, the issue of determining which part is eroding into the engine plume, and at what rate, becomes elementary by comparison. Since the OPAD potentially is sensitive to parts per billion of a given material [5], the amount of doping required should have a negligible effect on the properties of alloys used, but the potential for failure mitigation and reduction in operations costs could be significant.

3. SYSTEM EXTENSIONS [6,7]

To further expand hardware failure mitigation capabilities utilizing spectrographic data, and OPAD system data in particular, efforts to characterize, calibrate and independently measure large and small variations in bulk O/F have been undertaken. For the purpose of analyses, the SSME nozzle is used as a guide in building a first order model of the problem. Preliminary

estimates suggest sensitivity on the order of fractions of a percent change in total O/F relative to combustion fluctuations. The algorithm is believed extensible to other fuels, modification and additional parameters to address specific differing constituents and radiation sources. Furthermore, early analyses suggest in-nozzle optical access may be paramount to avoiding interferences due to particulates (soot) in hydrocarbon-based fuels such as RP-1 and in mitigation of background radiation issues.

At the high temperatures and pressures created inside the nozzle or in the shock structure, H2 – O2 combustion yields radiative emission in the UN-VIS-NIR primarily due to strong OH and H20 in the UV and NIR respectively. In addition, a blue – UV continuum is observed that is believed to emanate from an unstable excited electronics state of water vapor. Current efforts for O/F sensing will center around deriving a robust model for O/F, initially using the OH and UV-blue continuum which appear inseparable. No first-principle validated spectroscopic data models are known. The algorithm must separate OH from continuum and discriminate against changes in RPL or other flow-field condition.

Analyses will ensure bulk O/F is observed by careful selection of optical wavelength band transmittance for combustion active constituents. Other background sources may be present and require further models or design to minimize their obscuring effects. The effects of film cooling should be characterized if significant. While various techniques have traditionally been applied (e.g., line-by-line or radiation band methods), the analysis of OH is especially difficult, due to the many high overtones and suspected chemiluminescence.

The addition of neutron detectors or neutron spectrometers is a logical extension for the EDIFIS spectral processing software suite. Since much of the hardware interface is migrating to USB, the addition of new spectrometers is somewhat abstracted once the specific driver is written. The array processing capability of the EDIFIS suite is reusable for neutron and gamma particle detection.

Solid state detection of neutrons is currently of great interest, since there are numerous applications, but of primary interest for space is characterization of neutron flux in thermal, epithermal, and fast fission environments. Since the neutron has no charge, secondary reactions are employed. Detection is commonly performed using collisionally induced reactions with a thin film of the following species: $^{10}B(n,\alpha)^{7}Li$ and $^{6}Li(n,\alpha)^{3}H$. Reactions generally produce a high-energy particle and subsequently after collisions, a resultant space charge distribution. The available conduction electrons are then removed from the semiconductor as a small current which is related to the neutron rate, among other things.[8]

Neutron spectrometers are envisioned which use a hydrogen moderator to select various energy levels. These devices are solid state and shielded against non-desirable effects that might create errors, e.g. gamma rays or neutron particle sources.

4. CONCLUSIONS

As stated, we believe neutron detection is a natural capability to fold into the OPAD/EDIFIS tools. Current advancements in hardware should enable this transition to be brought about in a reasonably painless way. While other research is being pursued for neutron detection, the MSFC system offers unique capabilities accompanied by experience, testing and validation which position the tools for application to space flight and real-time performance. NASA's mandate to go to Mars is only one of the upcoming tasks which should benefit from this work.

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